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2 The Berkeley Accelerator Space Effects Facility (BASE) - A New Mission for the 88-Inch

3 Cyclotron at LBNL*

4 M.A. McMahan, Lawrence Berkeley National Laboratory

5 ABSTRACT: In FY04, the 88-Inch Cyclotron began a new operating mode that supports a
6 local research program in nuclear science, R&D in accelerator technology and a test facility for
7 the National Security Space (NSS) community (the U.S. Air Force and NRO). The NSS
8 community (and others on a cost recovery basis) can take advantage of both the light- and
9 heavy-ion capabilities of the Cyclotron to simulate the space radiation environment. A
10 significant portion of this work involves the testing of microcircuits for single event effects.
11 The experimental areas within the building that are used for the radiation effects testing are
12 now called the Berkeley Accelerator and Space Effects (BASE) facility. Improvements to the
13 facility to provide increased reliability, quality assurance and new capabilities are underway
14 and will be discussed. These include a 16 AMeV “cocktail” of beams for heavy ion testing, a
15 neutron beam, more robust dosimetry, and other upgrades.

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20 Corresponding Author: Margaret A McMahan

21 Lawrence Berkeley National Lab

22 MS88R0192, 1 Cyclotron Rd.

23 Berkeley, CA 94720

24 Fax: 510-486-7983; Phone: 510-486-5980; e-mail: p_mcmahan@lbl.gov

25 INTRODUCTION

26 The 88-Inch Cyclotron at Lawrence Berkeley Laboratory, operated by the University of
27 California for the US Department of Energy (DOE), is a K=140 sector-focused cyclotron with
28 both light- and heavy-ion capabilities. Protons and other light-ions are available at high
29 intensities (10-20 μA) up to maximum energies of 55 MeV (protons), 65 MeV (deuterons), 135
30 MeV (^3He) and 140 MeV (^4He). Most heavy ions through uranium can be accelerated to
31 maximum energies which vary with the mass and charge state.

32 The 88-Inch has a long history of providing beams for radiation effects testing. Early in
33 its forty-year history, it was realized that the variable frequency of the cyclotron translated to a
34 mass resolution of 1/3000, meaning that the cyclotron could separate most – but not all – ions of
35 near-identical mass-to-charge (m/q) ratio emanating from the ion source. [1] This was both a
36 blessing and a curse - a curse because there were a few beams that could never be delivered
37 uncontaminated, and a blessing for performing tasks such as detector calibrations or device
38 testing, for which several different beams could be delivered to an experiment with a minimum
39 of retuning. By the late 1970s, single event effect testing was occurring on a small scale. Some
40 effects discovered at LBNL by Aerospace Corporation include the first single event latchup
41 (SEL) (1979), the variation of SEL sensitivity with device temperature (1986) and single event
42 transients (SET) in digital devices (1987). [2]

43 Radiation effects testing with heavy ions using the 88-Inch came into its own when the
44 first electron cyclotron resonance (ECR) ion source was coupled to the Cyclotron in the early
45 1980s, the first such combination in the world. [3] With the ECR source, it was very easy to
46 ionize a mixture of noble gases to an integer m/q (2, 3, 4, 5) to make a “cocktail” of beams of

47 near-identical m/q . [4] This proved very beneficial in the SEE studies since users could switch
48 from ion to ion with a minimum of tuning time. Cyclotron staff developed a “light-ion cocktail”
49 of fully-stripped $m/q=2$ ions (through ^{36}Ar) and a “heavy-ion cocktail” of $m/q = 5$ at 4.5 AMeV.
50 This latter cocktail was available through xenon from the LBNL ECR.

51 In the early 1990s, the ion source group built a second state of the art ECR source, the
52 Advanced ECR (AEER) source. [5] With this source it was possible to obtain Bi^{+41} , which at
53 $m/q = 5.1$, could be accelerated together with the 4.5 AMeV cocktail. At a linear energy transfer
54 (LET) value of 98 MeV/mg/cm^2 , this was very useful for testing radiation-resistant electronics.
55 Throughout the decade of the 1990s, improvements were made in the ion sources and cyclotron
56 vacuum which benefited both the nuclear science and radiation effects users alike. A new
57 cocktail was developed at 10 AMeV, which allowed ions as heavy as xenon to penetrate silicon
58 to depths of greater than $100 \mu\text{m}$; this was important because chips were becoming increasingly
59 more complex and difficult to delid. The amount of radiation effects testing performed at the
60 Cyclotron with either heavy ions or protons increased steadily to 15-20% of the scheduled time,
61 or about 1000-1200 hours/year.

62 In 2003, the DOE announced plans to close the 88-Inch Cyclotron as a DOE National
63 User Facility in FY04. This was a major blow to heavy ion testing in the United States, as neither
64 of the other facilities at Brookhaven National Lab or Texas A&M University could replace what
65 was being done at Berkeley. The US Air Force Space Missile Command (USAF-SMC) and
66 National Reconnaissance Office (NRO) came to the rescue, signing a Memo of Understanding
67 with DOE to provide 40% of the operating funds of the Cyclotron in FY04 and FY05; DOE
68 agreed to continue funding the Cyclotron at the 60% level. Thus the 88-Inch Cyclotron was
69 reborn with a dual mission: 1) an in-house basic research program in nuclear science to serve

70 LBNL and UC Berkeley scientists and students, and 2) a state-of-the-art, multifaceted radiation
71 effects facility – the Berkeley Accelerator Space Effects (BASE) Facility - to serve the National
72 Space Security community funded by USAF-SMC and NRO. When time is available, the BASE
73 facility is also used by commercial and other government agencies on a cost recovery basis and
74 for LBNL experiments in radiation biology. In addition, a neutron beam line has been funded by
75 a DOE-NNSA Academic Alliance grant to measure neutron cross sections on unstable targets for
76 stockpile stewardship and nuclear astrophysics.

77 THE BASE FACILITY

78 The layout of the 88-Inch Cyclotron facility and the beamlines which are part of BASE is
79 shown in Figure 1. Heavy ion testing takes place in the vacuum chamber located in Cave 4B.
80 Three heavy ion cocktails have been developed at energies of 4.5, 10 and 16 AMeV and are
81 summarized in the first three rows of Table 1. The 16 AMeV cocktail is a recent addition and is
82 available through krypton, at an LET of 26 MeV/mg/cm² and a range of almost 700 μm . [6] It is
83 possible to run this cocktail in air if needed although the energy at the DUT will be degraded to
84 ≈ 9 AMeV. For each listed cocktail, a group of standard ions are listed which are regularly
85 available.

86 LET versus Range in Si is plotted in Figure 2 for four cocktail energies plus a few of the
87 more commonly used light ion tunes. Several orders of magnitude are available in both range and
88 LET, making the BASE test facility very versatile.

89 Several improvements to the BASE facility are in progress or planned. For the heavy ion
90 test facility, the control system and user interface has been converted to a PC-based
91 LABVIEW™ system from the original Macintosh system written at Aerospace Corporation. This

92 will allow the 88-Inch staff to maintain and upgrade both the hardware and software. The new
93 system was implemented in September and is undergoing beta-testing.

94 In addition, we have been investigating ways to implement a more reliable and robust
95 dosimetry system. The present dosimetry system, consisting of plastic scintillator, is not very
96 radiation hard. With a combination of increased use, more use of high-energy cocktails, and
97 more use of higher doses of high-LET ions such as xenon and bismuth, the scintillators have
98 been degrading over time, sometimes within a few hours. We have been testing an inorganic
99 scintillator, YAP(Ce), which has been shown for electrons to be 10-100x more radiation resistant
100 than organic scintillators such as plastic. Little data is available for heavy ions. We are testing it
101 for our application and, based on initial performance, anticipate replacing all the plastic in the
102 next few months. Another limitation to the dosimetry is saturation of the system at levels of <
103 10^5 ions/second for the heaviest ions. The cause of this is under investigation.

104 A third improvement to the heavy ion test facility is planned for next year. We expect to
105 incorporate a memory chip which has a well characterized SEU cross section curve. This chip
106 will be on a lever arm inside the chamber so it can be dropped in front of the DUT and give a
107 check on whether the upset cross section is within certain preset limits; this will insure that all
108 aspects of the beam delivery and dosimetry are working correctly.

109 The Light Ion Irradiation Facility (LIIF) is presently located in Cave 3 but is being
110 moved to Cave 4A. This will allow better access and convenience, being adjacent to the Heavy
111 Ion Facility. The LIIF is set up to run samples in air. The beam is 10 cm in diameter and a
112 transmission ion chamber is used to tune a uniform beam and to perform dosimetry. The facility
113 can be used for protons from 13.5-55 MeV, other light ions, and the light ion cocktail. The
114 energy loss in the ion chamber limits lower energy running in this facility. For instance, the 13.5

115 MeV proton beam degrades to 9 MeV at the DUT position. It's possible to go to lower energies
116 in this beam line if other means of dosimetry are employed.

117 A neutron capability is being developed at the Cyclotron which will be available for
118 radiation effects testing. In Phase 1, to be finished in 2005, a white spectrum of neutrons will be
119 available for RET. Neutron dosimetry is being developed for this application. In Phase 2, quasi-
120 monoenergetic beams will be available in the range of 10-32 MeV, as well as a beam around 200
121 keV. These energies of beams are useful for ground based soft error studies and for studies
122 related to lunar and Martian surface enclosures, e.g. shielding studies, radiation biology and
123 radiation effects on materials and electronics.

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125 REFERENCES:

126 [1] Bernard G. Harvey, Nuclear Spectroscopy and Reactions, Part A, Academic Press, Inc
127 (1974).

128 [2] Lawrence Greenberg, private communication (2004)

129 [3] C.M. Lyneis, Proc. 11th Intl Conf on Cyclotrons and their Applications, Tokyo, JP, pg 707
130 (1987).

131 [4] M.A. McMahan, et. al., Nucl. Instr. Meth. A253, 1 (1986).

132 [5] Z.Q. Xie, Rev. Sci. Instrum. **69**. 625 (1998).

133 [6] M.A. McMahan, in: Proc. of Data Workshop for Nuclear Science Radiation Effects Conf.,
134 (2004)

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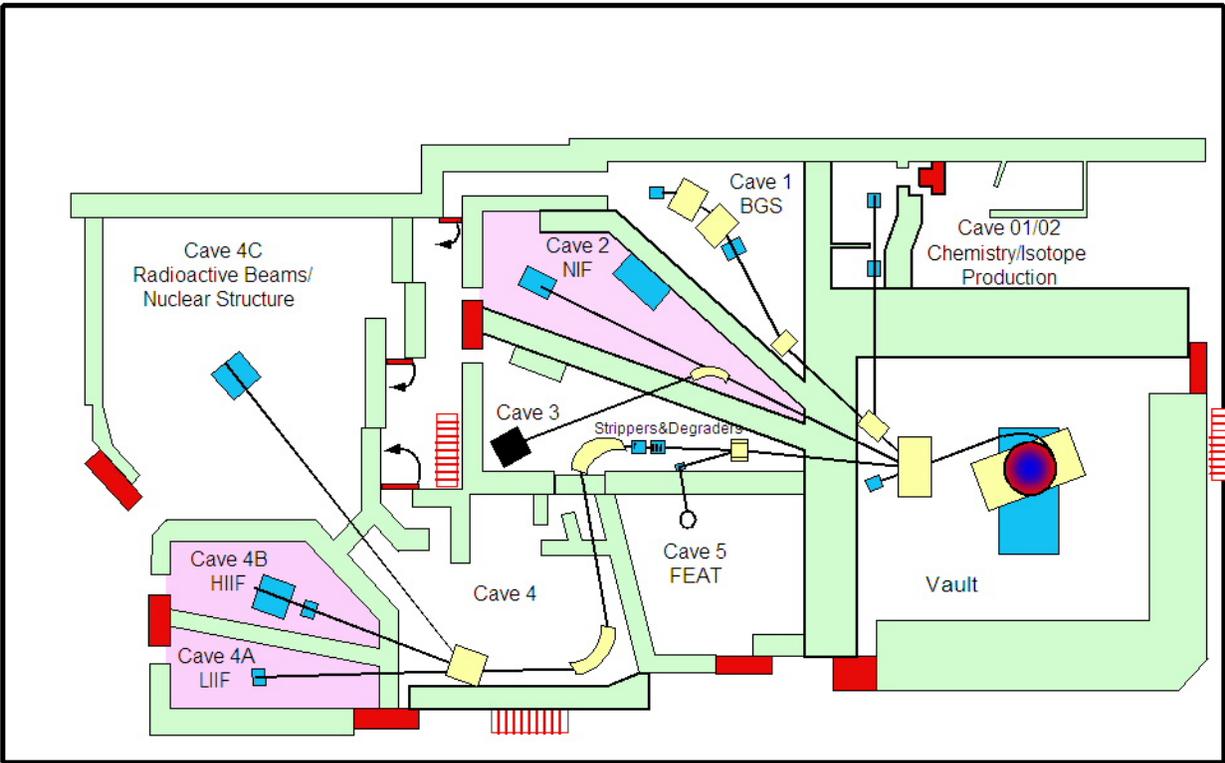
136 Table 1. Summary of standard BASE cocktails and other beams. Other ions and energies are
 137 available by special arrangement.

| Cocktail (AMeV) | Standard Ions (st) | Other Ions ^a | LET (MeV/mg/cm ²) | Range in Si (μm) |
|-----------------|--|---|-----------------------------------|-----------------------------|
| 4.5 | ¹⁵ N, ²⁰ Ne, ⁴⁰ Ar, ⁵⁹ Co, ⁶³ Cu, ⁸⁶ Kr, ¹³⁶ Xe | HeH ^b , ¹⁰ B, ⁷⁸ Kr, ²⁰⁹ Bi | 3.1-68.8 (st) 0.064-99.6 (all) | 43-67 (st) 41-180 (all) |
| 10 | ¹⁸ O, ²² Ne, ⁴⁰ Ar, ⁶⁵ Cu, ⁸⁶ Kr, ¹³⁶ Xe | ¹⁰ B, ²⁷ Al, ⁵¹ V, ⁷³ Ge, ⁹⁸ Mo | 2.2-59.1 (st) 0.89-59.1 (all) | 97-227 (st) 98-307 (all) |
| 16 | ¹² C, ¹⁴ N, ¹⁷ O, ²⁰ Ne, ⁴⁰ Ar, ⁶³ Cu, ⁷⁸ Kr | ²⁸ Si, ³⁵ Cl, ⁵⁵ Mn, | 0.93-25.7 (all) | 171-467 (all) |
| 32.5 | ⁴ He, ¹² C, ¹⁴ N, ¹⁶ O, ²⁰ Ne, ³⁶ Ar ¹⁸⁺ | ² H, H ₂ ^b , ²⁸ Si, ³² S, ⁴⁰ Ca | 0.022-8.01 | 0.29-4.29 mm |
| Light Ion Tunes | ¹ H, ⁴ He | | 0.009-0.342 | 93.4-14,430 |

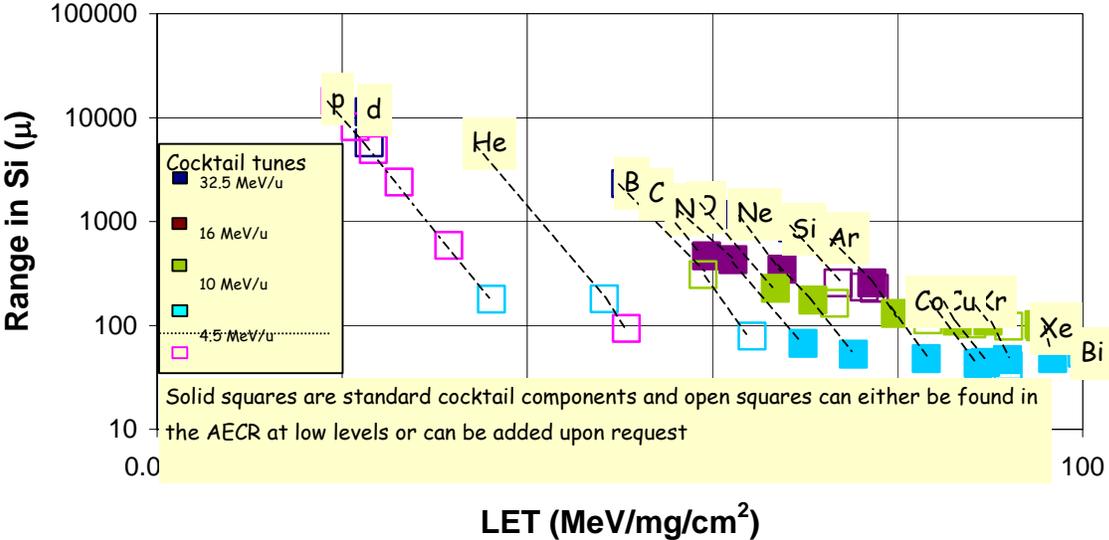
138 ^a These ions require special arrangements and advance notice.

139 ^b LETs and Ranges for molecular ions are calculated for separate components after break-up in
 140 target or scattering foil.

Figure 1. Map of 88-Inch Cyclotron Facility. The shaded areas are the beamlines which are used now or will be used in the future for BASE.



LET vs Range - 88" Cyclotron BASE Facility



141
 142 Figure 2. Range versus LET for all LBNL cocktail tunes and other standard beams for radiation
 143 effects testing.